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AIR FORCE SURVEYS IN GEOPHYSICS, NO. 435



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Almost-Necessary Conditions for a Solar Active Region to Produce a Subsequent Polar Cap Absorption Event

EDWARD W. CLIVER

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17 April 1980

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SPACE PHYSICS DIVISION PROJECT 4643
AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MASSACHUSETTS 01731

AIR FORCE SYSTEMS COMMAND, USAF



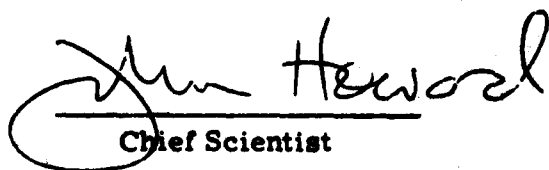
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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFGL-TR-80-0151	2. GOVT ACCESSION NO. AD-A088882	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ALMOST-NECESSARY CONDITIONS FOR A SOLAR ACTIVE REGION TO PRODUCE A SUBSEQUENT POLAR CAP ABSORPTION EVENT	5. TYPE OF REPORT & PERIOD COVERED Scientific. Interim.	
7. AUTHOR(s) Edward W. Cliver	6. PERFORMING ORG. REPORT NUMBER AFSG No. 425	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Geophysics Laboratory (PHP) Hanscom AFB Massachusetts 01731	8. CONTRACT OR GRANT NUMBER(s) 117 APR 80	
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Geophysics Laboratory (PHP) Hanscom AFB Massachusetts 01731	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62101F 46430306	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) AF - T - 282 AF - AT - 125	12. REPORT DATE 17 April 1980	
	13. NUMBER OF PAGES 20	
	15. SECURITY CLASS. (of this report) Unclassified	
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE	
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Solar radio bursts Proton events Polar cap absorption events Longitudinal distribution of PCA flares U-shaped spectra Non-U solar bursts Solar active regions		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Between 1955 and 1976, 133 polar cap absorption (PCA) events with unambiguous solar flare associations were observed. Over one-fourth of these events (35/133) originated in solar active regions that had already produced a PCA. More significantly, these "subsequent" PCA's included 35 percent (26/74) of all the principal (≥ 2.0 dB) PCA's in this sample. In this paper, we establish quantitative criteria to distinguish between those solar active regions that are likely to produce such subsequent absorption events and those that pose no further threat to high latitude HF or VLF communications.		

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These criteria are based on flare solar disk position and the ¹8800 MHz burst peak flux density.

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Preface

Previous efforts by the Solar Radio Section, AFGL, have focused on the prediction of Polar Cap Absorption (PCA) events based on the radio burst emission of the responsible flare. This ordinarily gives lead times ranging from minutes to hours during which communicators who use high-latitude HF circuits can be notified. For certain applications, longer lead times are desirable. Hence, the NOAA-AWS Forecast Centers currently issue joint forecasts of the probability of a PCA event occurring during each of the next three 24-hour periods. In this study we have considered "persistence" forecasting of PCA events as a first step toward providing such intermediate-range forecasts. The rules-of-thumb or statistical guidelines we developed are presented as "stand-alone" criteria; however, we know that in practice they will be combined with all other pertinent information received at the forecast center to arrive at the eventual forecast.

I am grateful to Bill Barron, Don Guidice, Peggy Shea, and Don Smart for helpful discussions and critical readings of the manuscript. My efforts in this work are dedicated to my parents.

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Almost-Necessary Conditions for a Solar Active Region to Produce a Subsequent Polar Cap Absorption Event

1. INTRODUCTION

1.1 PCA Effects

Energetic (≈ 5 MeV) protons emitted by large solar flares can disrupt HF and VLF communications in the earth's polar regions for periods of days. Cormier¹ reported a mean duration of 63.6 hours for a sample of 29 (> 0.5 dB) polar cap absorption (PCA) events observed at Thule between 1962 and 1972. One of these events lasted 203 hours, with 30 MHz riometer absorption ≥ 2.0 dB for nearly 5 consecutive days. In early August 1972, the ≥ 2.0 dB loss condition persisted for over 6 days, although at least three major flares were responsible for this disturbance. Advance warning of PCA events can help to mitigate the serious difficulties they present to high latitude radio communicators.

1.2 Persistence

Persistence in solar flare occurrence, that is, the tendency for flares to occur in active regions that have already produced flares, has long been recognized as an

(Received for publication 16 April 1980)

1. Cormier, R. J. (1973) Thule Riometer Observations of Polar Cap Absorption Events (1962-1972), AFCRL-TR-73-0060, AD A762279.

important consideration in flare forecasting (Zirin,² Smith,³ and Cliver et al⁴). The purpose of the research reported here was to investigate the usefulness of a persistence technique for the forecasting of parent flares of PCA events. In other words, we will attempt to answer the question: "Given that a PCA parent flare has occurred in a solar active region, what is the likelihood of a follow-on event from the same region?" Such a technique is worthy of consideration because over one-fourth (35/133) of all PCA's occurring between 1955 and 1976 that could be confidently linked to a solar flare (those events that we could reasonably hope to predict) originated in solar active regions that had already produced a PCA flare. We shall refer to these follow-on events to which we address this study as "subsequent" PCA's.

1.3 Overview

In Section 2 we list the data sources from which we compiled our statistics, in Section 3 we discuss the characteristics of subsequent PCA's, and in Section 4 we present criteria for distinguishing between those active regions that are likely to produce subsequent PCA's and those that are unlikely to cause further proton-induced geophysical disturbances. These criteria are based on: (1) the solar longitude of PCA parent flares and (2) the flare-associated ≥ 8800 MHz peak flux density. In Section 5 we discuss the applicability of these criteria as both "null" and positive predictors of subsequent PCA events.

2. DATA SOURCES AND CONSIDERATIONS

The lists of PCA events with responsible flare associations that we used were taken from the following sources: Catalog of Solar Particle Events, 1955-1969 (eds. Švestka and Simon⁵); reports compiled by Dodson et al^{6,7} to extend the Catalog through 1972; and the published lists of Castelli and Barron⁸ and Castelli and Tarnstrom.⁹ For events occurring after 1965, supplemental microwave data were obtained from the IAU's Quarterly Bulletin of Solar Activity and from Solar Geophysical Data.

A polar cap absorption event, as indicated by a measurable (≥ 0.3 dB) increase on a sunlit polar riometer, may be associated with a solar flare, the sudden commencement of a geomagnetic storm, or a recurrent 27-day geomagnetic disturbance. In this study we considered only those PCA's with the highest confidence flare associations. For all but 10 of the events (those occurring after 1972), the associations were made by Drs. Dodson and Hedeman. In regard to the absorption events (Due to the large number of references cited above, they will not be listed here. See References, page 19.)

themselves, we eliminated seven "weak" f-min events (detected by polar ionosondes) which had unambiguous flare associations but which lacked a verifying riometer absorption measurement (Smart et al¹⁰).

Before we proceed, it must be cautioned that although we have used the largest (and cleanest) data set available, all conclusions we reach are necessarily bound by the statistics of small numbers. Nevertheless, it is hoped that the results presented can aid in the solution of an important forecast problem.

3. CHARACTERISTICS OF SUBSEQUENT PCA's

Figure 1 is a histogram showing the number of active regions that generated a given number of PCA parent flares between 1955 and 1976. As can be seen, a wide majority (78/98 or 80 percent) of all PCA producing regions account for only a single event. Thus, persistence in itself would be a very poor predictor of subsequent events. For example, if we postulated that every PCA would be followed by a subsequent event, our ultimate false alarm rate would approach 75 percent (98/133 for this sample). In Section 4 we will show that information contained in the PCA flare (other than the bare fact of its occurrence) can be used to complement persistence and aid in the prediction of subsequent PCA's.

Figure 2 shows that subsequent PCA's make up an increasing percentage of the total number of similar size PCA's as we consider successively larger classes of events. In fact, six of nine of the ≥ 20 dB PCA's were subsequent events. Also we note that 35 percent (26/74) of the flare-associated, principal (≥ 2.0 dB) absorption events occurring during the 19th and 20th solar cycles originated in active regions that had generated a previous PCA event.

Figure 3 (a-c) is a series of histograms for delay times between pairs of PCA parent flares originating in the same active region. In Figure 3a the displayed separations are between the first and second observed parent flares from each active region. In Figure 3b the separations between higher-order PCA parent flares are plotted, and Figure 3c is a composite. Because of the small sample sizes involved, it is difficult to draw confident conclusions from these histograms. We do note from Figure 3c that all but one of the flares responsible for a subsequent PCA event occurred within 6 days (≈ 80 degrees) of the preceding proton flare. The PCA parent flares from McMath 13225 in September 1974 were separated by just over 9 days.

10. Smart, D. F., Shea, M. A., Dodson, H. W., and Hedeman, E. R. (1976) Distribution of proton producing flares around the sun, Space Research XVI:797-802.

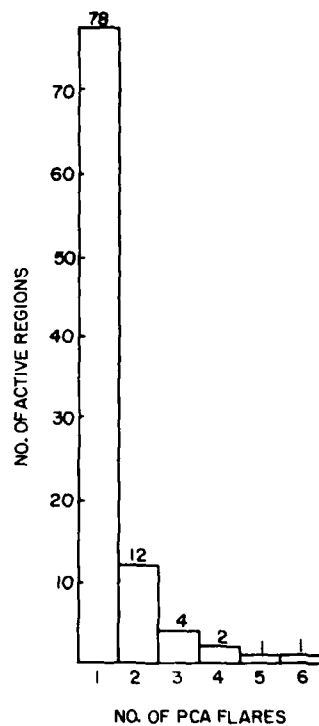


Figure 1. The Number of Solar Active Regions Generating a Given Number of PCA Parent Flares, 1955-1976 (Sample size = 133 events)

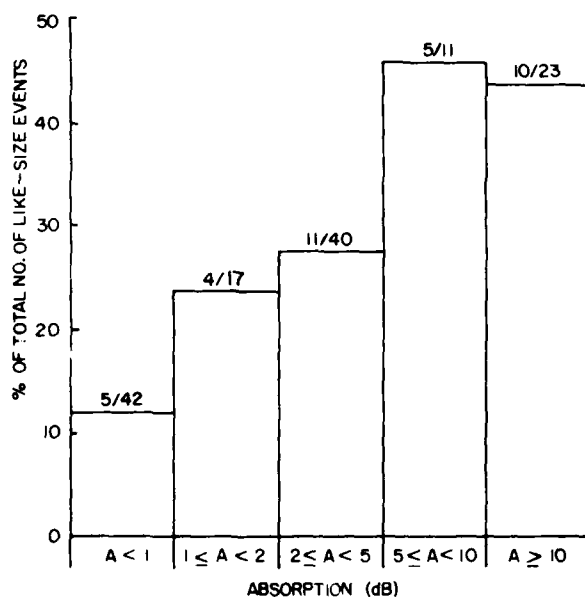
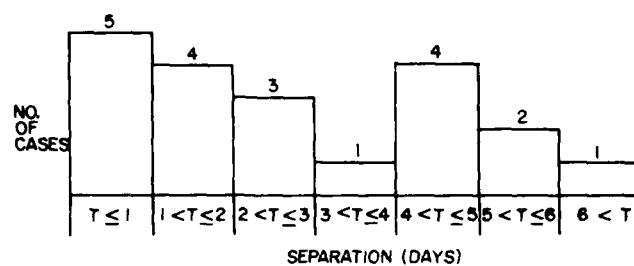
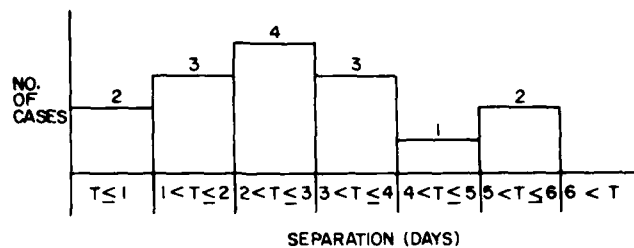


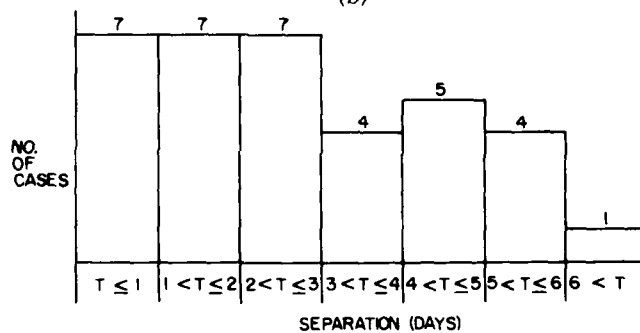
Figure 2. Percentages of Classes of Various Sized PCA's Which Were Subsequent Events, 1955-1976



(a)



(b)



(c)

Figure 3. Separation Between Pairs of PCA Parent Flares. (a) The separation T in days between the first and second PCA parent flares from an active region, 1955-1976, (b) The separation T between higher order pairs of subsequent PCA parent flares from an active region, and (c) The composite of (a) and (b)

4. STATISTICAL CRITERIA

4.1 Position of the Flare on the Solar Disk

In Figure 4a we have displayed the disk position of the initial parent flare from all active regions that were unambiguously associated with at least one PCA event

between 1955 and 1976, distinguishing between those regions that generated subsequent PCA's ("multiple event" regions) and those that did not ("single event" regions). The statistical imbalance for solar longitude $\geq 60^\circ$ W is striking. We expected some diminution in the numbers of multiple event regions as we approached the western limb, because the subsequent events would begin to occur behind the limb. To quantify this expectation, consider Figure 3a which shows the separation between the initial pairs of PCA's from an active region. If we assume that the "average" PCA parent flare in the westernmost sector occurred at 75° W, then we would expect to see all of the subsequent parent flares occurring within a day of the initial event (25 percent or 5/20 from Figure 3a) plus roughly half of those with delay times between 1 and 2 days (10 percent, 2/20). In other words, we would expect a 65 percent reduction in the apparent occurrence of initial PCA parent flares from multiple event regions within this sector. The longitudinal distribution of initial PCA parent flares from multiple event regions observed between 1955 and 1976 is rather flat east of 60° W, with an average value of four such flares per 30° sector. Assuming that four such events were also generated in the westernmost sector during this time period, we would expect from the above analysis to observe only ≈ 1 , in good agreement with the zero actually observed.

In addition, no multiple event region generated more than one observable subsequent parent flare at longitudes $\geq 60^\circ$ W. Ten of these regions produced their last observed event in this sector. Again, this is what we would expect. First of all, from Figure 1 we note that only 40 percent (8/20) of multiple event regions generated more than two PCA's. Secondly, if we consider Figure 3d, we note the tendency for higher-order pairs of subsequent PCA parent flares to have separations > 2 days. Proceeding as above, we would estimate that, at most, one multiple region ($0.4 \times 10 \times 3.5/15 \approx 0.9$) would have generated more than one PCA parent flare at $\geq 60^\circ$ W solar longitude, in reasonable agreement with the observations.

We checked this western hemisphere disparity by expanding the sample size to include all Catalog events (excluding those in the Catalog Appendix) with certain or probable flare associations. Since the lower threshold for inclusion in the Catalog is $0.1 \text{ proton (cm}^2 \text{ s ster)}^{-1}$ before December 1965 (Pioneer 6) and $0.01 \text{ proton (cm}^2 \text{ s ster)}^{-1}$ after, this admitted a large number of additional events. The results are shown in Figure 4b where we see that the imbalance persists.

Our first "almost necessary" condition, then, is:

For a solar active region to produce a subsequent absorption event, it must have generated its previous PCA parent flare east of 60° W.

This solar longitude criterion applies whether the previous PCA parent flare was the initial major flare from that region or an earlier subsequent PCA parent flare.

	E90	E60	E30	0	W30	W60	W90
"SINGLE EVENT" REGIONS	7	9	11	15	20	16	
"MULTIPLE EVENT" REGIONS	4	5	4	4	3	0	

(a)

	E90	E60	E30	0	W30	W60	W90
"SINGLE EVENT" REGIONS	16	22	19	29	26	43	
"MULTIPLE EVENT" REGIONS	14	21	12	13	14	1	

(b)

Figure 4. Solar Longitude of PCA Parent Flares. (a) The location of the initial PCA parent flare from each active region that generated at least one such flare, distinguishing between those regions that produced subsequent absorption events ("multiple" regions) and those that did not ("single" regions), 1955-1976. (b) Similar to (a) except we are now considering all particle events before December 1965 with fluxes > 0.1 proton $(\text{cm}^2 \text{s ster})^{-1}$ for energies > 10 MeV and all particle events after December 1965 with fluxes > 0.01 proton $(\text{cm}^2 \text{s ster})^{-1}$ at these energies. Also, the flare association criterion has been lowered from definite to probable. (We excluded particle events with probable associations with behind-the-limb active regions for which no flare activity was reported. There were four such cases beyond the west limb)

4.2 8800 MHz Burst Peak Flux Density Criterion

Castelli and Guidice¹¹ distinguished between two classes of proton flares—those characterized by the well-known, U-shaped, peak-flux-density radio spectrum with intensities exceeding 1000 sfu (1 sfu = 1 solar flux unit = $10^{-22} \text{W m}^{-2} \text{Hz}^{-1}$) in the

11. Castelli, J. P., and Guidice, D. A. (1976) Impact of current solar radio patrol observations, Vistas in Astronomy 19:355-384.

meter wavelength range and at frequencies ≥ 8800 MHz (O'Brien¹²), and those associated with long-duration, moderate-intensity (50-100 sfu) microwave bursts. Castelli and Tarnstrom⁹ developed these ideas further. To determine if either type of proton flare was generally associated with solar active regions that were likely to produce subsequent events, we prepared histograms of the number of PCA flares that produced a given burst peak flux density at a frequency ≥ 8800 MHz, distinguishing between those flares that were followed by a subsequent PCA parent flare (Figure 5b) and those that were not (Figure 5a). In both cases the abscissa is the logarithm of the maximum burst peak flux density recorded by any observatory at any frequency ≥ 8800 MHz. (The meaning of the "x'ed" boxes will be discussed in Section 5.) The vertical dashed line is drawn at the 1000 sfu level. We note that 37 of the 45 (82 percent) PCA parent flares occurring between 1955 and 1976 with ≥ 8800 MHz burst emission less than this level (to the left of the dashed line) were not followed by subsequent PCA parent flares. Conversely, 38 percent (27/71) of the flares to the right of the 1000 sfu line preceded subsequent PCA flares. Our second "almost necessary" condition is:

For a solar active region to generate a subsequent absorption event, the radio emission associated with the previous PCA parent flare from that region must have exceeded 1000 sfu at a frequency ≥ 8800 MHz.

It was wondered if other, more general, flare characterizations (than a single frequency peak flux density) might have even greater utility for distinguishing between those regions likely to erupt violently again and those unlikely to cause further PCA's. In particular, the Comprehensive Flare Index (CFI) developed by Dodson and Hedeman¹³ was considered. In addition to its importance, this index is based on flare X-ray and radio (both meter and cm wavelength) emission. CFI values range from zero for subflares to from 15 to 17 for flares that are outstanding in each of the wavelength regimes. Figures 6a and 6b are analogous to Figures 5a and 5b, except that in Figure 6 we used the CFI as the abscissa. Inspection shows that for a comparable number of missed events, the ≥ 8800 MHz burst peak flux density criterion and the CFI produce identical results for this application. Of significance for a real-time operation, the ≥ 8800 MHz flux densities are reported directly by the observatories and require no further computation.

12. O'Brien, W. E. (1970) The Prediction of Solar Particle Events Based on Solar Radio Emissions, AFCRL-TR-70-0425, AD A875024.
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14. Dodson, H. W., and Hedeman, E. R. (1975) Experimental Comprehensive Solar Flare Indices for Certain Flares, 1970-1974, WDC - A Report UAG-52, NOAA, Boulder, CO.

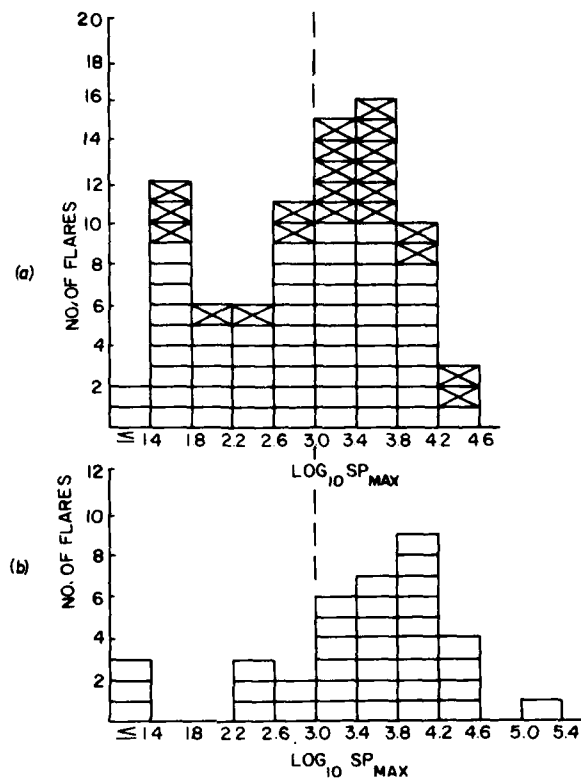


Figure 5. The Number of PCA Parent Flares With a Given Maximum Burst Peak Flux Density (S_p) at Frequencies ≥ 8800 MHz. None of the events in (a) were followed by subsequent PCA parent flares. All of the events in (b) preceded subsequent events. The dashed vertical line is drawn at $S_p = 1000$ sfu. The checked boxes in (a) refer to flares occurring at solar longitudes $> 60^\circ$ W. High frequency microwave burst data were not available for 17 events

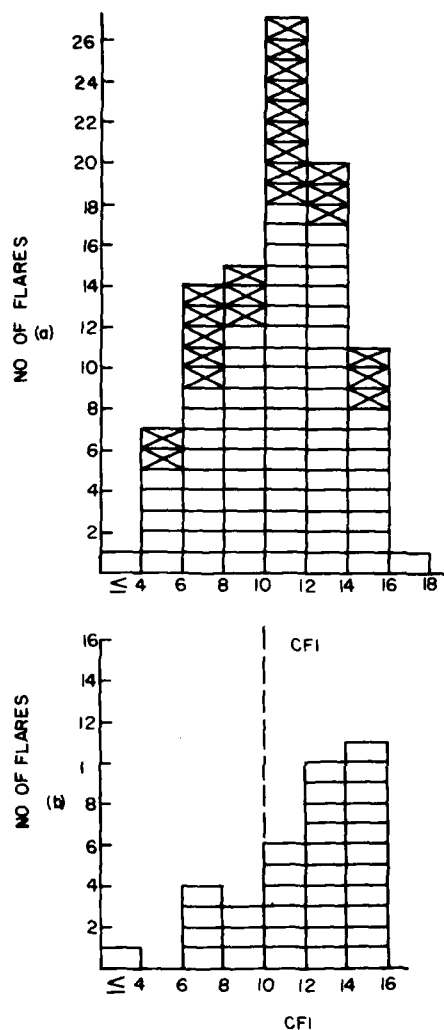


Figure 6. The Number of PCA Flares With a Given Comprehensive Flare Index (CFI). The flares in (b) were followed by subsequent events while those in (a) were not. The dashed vertical line is drawn for comparison with Figure 5. Data were not available for two events

5. APPLICATION

5.1 "Null" Forecast

A "null" forecast specifies that a given event will not occur during a specified time period. During solar minimum a null forecast for PCA events would generally be of little value. However, a null forecast of proton activity when a region with the demonstrated ability to produce PCA events is on the solar disk is more significant. The two conditions presented in this paper can be used to make such forecasts. Between 1955 and 1976, 78 solar active regions generated a solitary

PCA event. The solar longitude criterion could have been used to rule against subsequent PCA's from 16 of these regions and the ≥ 8800 MHz criterion would have discriminated against at least an additional 27 regions (high frequency microwave data were not available for 11 events). On the negative side, six null forecasts would have been "busted" by the occurrence of a subsequent event, for a forecast accuracy of 86 percent (43/49). (It would be a specious argument to say that this represents only marginal improvement over an accuracy of 80 percent (78/98) obtained by postulating that no initial PCA parent flare will be followed by a subsequent event, since the additional "missed" forecasts would not be acceptable.) In addition, the two conditions could have been used to correctly predict that the final PCA parent flare had occurred in multiple event regions for 13 of the 20 cases, with 2 misses (87 percent).

5.2 Positive Forecasts

Since the two criteria developed above show some promise when used as necessary conditions for the purpose of issuing null forecasts, it is natural to question whether or not they might also be used as sufficient conditions to issue positive forecasts. In other words, what is the likelihood of a subsequent event occurring when the previous PCA parent flare from the region occurred east of 60° W and had burst peak flux densities in excess of 1000 sfu at frequencies ≥ 8800 MHz? To answer this question, let us consider Figure 5 again. The "x'ed" boxes in Figure 5a refer to events that occurred at solar longitudes $\geq 60^\circ$ W. The unchecked boxes to the right of the dashed line in Figure 5a would thus be false alarms, since they refer to PCA flares that met our two criteria, but were not followed by subsequent events. The forecast accuracy for this method would be 48 percent (27/56), a significant improvement over the 29 percent figure (35/120) obtained by assuming that all PCA flares occurring east of 80° W will be followed by subsequent events. The "catch" is that in order to approach 100 percent accuracy for a 50 percent probability forecast, we would have to extend the forecast period to 6 days (Figure 3c), an uncomfortably long period of time. There may be special circumstances where such an extended forecast is appropriate—for example, scheduling activities for a space shuttle mission or planning a high-latitude exercise dependent on HF communications—especially when one considers that the condition being forecast, a polar cap absorption event, can last for a significant fraction of the forecast period. (For comparison, consider a 24-hr probability forecast for a Class M flare.) In general, however, a 6-day forecast does not have wide applicability and the greatest benefit from the techniques developed here should stem from their use as "almost necessary" conditions for the purpose of issuing null forecasts of subsequent PCA events.

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